

Neutrinoless Double Beta Decay in Particle Physics

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Abstract

Neutrinoless double beta decay is a process of fundamental importance for particle physics. It can be mediated by light massive Majorana neutrinos (*standard interpretation*) or by something else (*non-standard interpretations*). We review its dependence on the neutrino parameters, its complementarity to other observables sensitive to neutrino mass, and emphasize its ability to distinguish different neutrino mass models. Then we discuss mechanisms different from light Majorana neutrino exchange, and show what can be learned from those and how they could be tested.

Keywords: lepton number violation, neutrino mass, double beta decay

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) experiments [1] are much more than neutrino experiments. Searches for $0\nu\beta\beta$ are fundamental physics because they probe the presence of lepton number violation, which is on equal footing to baryon number violation, i.e. proton decay. Once a (positive or negative) result from $0\nu\beta\beta$ experiments is present, one can go on and (assuming that lepton number is violated in Nature) interpret the outcome in two ways:

1. *Standard Interpretation:*

neutrinoless double beta decay is mediated by light, active and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution;

2. *Non-Standard Interpretations:*

neutrinoless double beta decay is mediated by some other lepton number violating process, and light, active and massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution.

In the first interpretation $0\nu\beta\beta$ is a neutrino physics experiment, in the second one a broader particle physics experiment with emphasis on the particular lepton number violating physics under study. Of course, the observation of $0\nu\beta\beta$ implies the Majorana nature of neutrinos (to be precise, a tiny 4-loop induced Majorana mass term), a fact known as the black-box, or Schechter-Valle, theorem [2].

We will discuss in this contribution some of the physics potential of the two interpretations given above. For experimental aspects, see the contributions in [1], nuclear physics issues are dealt with in [3].

2. Standard Interpretation

The first interpretation is most common, and in the light of neutrino oscillations arguably the best motivated one. Assuming light massive Majorana neutrino exchange, the amplitude for $0\nu\beta\beta$ is proportional to

$$\mathcal{A} \propto G_F^2 \frac{\langle m_{ee} \rangle}{q^2} \quad \text{with} \quad \langle m_{ee} \rangle \equiv \left| \sum U_{ei}^2 m_i \right| = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta} . \quad (1)$$

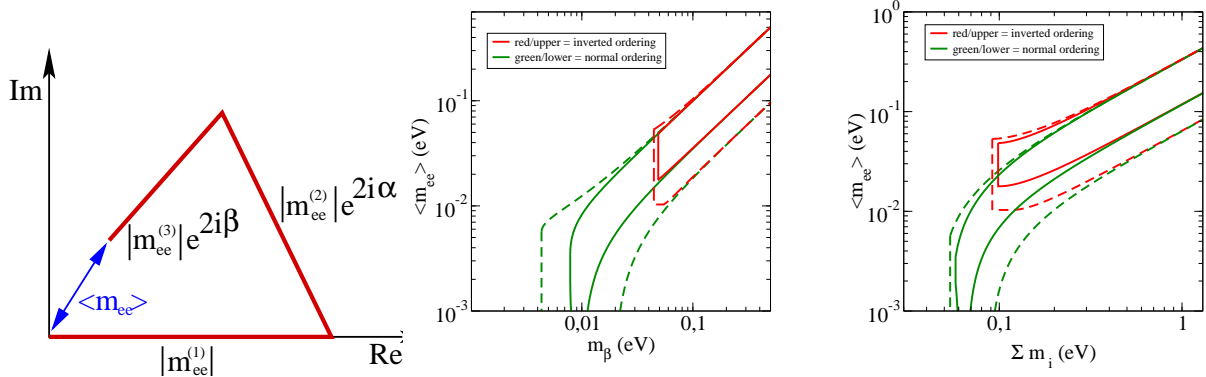


Figure 1: Left: geometrical interpretation of the effective mass. Middle: effective mass vs. m_β . Right: effective mass vs. sum of masses. Both the best-fit values and the 3σ ranges of the oscillation parameters are used.

Here $q^2 \simeq (0.1 \text{ GeV})^2$ is the typical momentum exchange in the reaction, m_i are the neutrino masses, $|U_{ei}|$ the PMNS matrix elements of the first row (depending on θ_{12} and θ_{13}) and α, β are the two Majorana phases. The coherent sum $\langle m_{ee} \rangle$ is usually called the effective mass and contains 7 of 9 parameters of the neutrino mass matrix, which in the fundamental Lagrangian fully describes neutrino mass and lepton mixing. Two of those 9 parameters, the Majorana phases, show up only in the effective mass. It contains therefore a large amount of information. Its geometrical interpretation is shown in the left part of Fig. 1: if the three complex terms in $\sum U_{ei}^2 m_i$ cannot form a triangle, the effective mass is non-zero. Fig. 1 also displays plots of the effective mass versus the other two complementary mass observables. Those are

$$m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2} \quad \text{and} \quad \sum m_i = m_1 + m_2 + m_3, \quad (2)$$

measurable in beta decays [4] and in cosmology [5], respectively. We refer to the cited contributions presented at this conference for their current status and future prospects.

What is noteworthy from the plots of neutrino mass observables is that the effective mass can vanish in case of the normal neutrino mass ordering. While it seems at first sight unnatural that 7 parameters conspire in order to let a particular combination of them become zero, it should be kept in mind that $\langle m_{ee} \rangle$ is the ee element of the fundamental low energy Majorana neutrino mass matrix. This matrix is generated by the underlying theory of mass generation, and texture zeros occur frequently in such (flavor) models. We recall here that the dependence on $\langle m_{ee} \rangle$ of the amplitude is in fact stemming from the term $\sum U_{ei}^2 m_i / (q^2 - m_i^2)$, and the limit $q^2 \gg m_i^2$ is taken in the fermion propagator to obtain Eq. (1). If $\sum U_{ei}^2 m_i = 0$, then there is a term of order $U_{ei}^2 m_i^3 / q^4$, which will in general not vanish. It is however suppressed by a factor $m_i^2 / q^2 \lesssim 10^{-16}$.

In contrast to the normal ordering, the effective mass cannot vanish for the inverted mass ordering. The lower limit of $\langle m_{ee} \rangle$ can be expressed as

$$\langle m_{ee} \rangle_{\min}^{\text{IH}} = (1 - |U_{e3}|^2) \sqrt{|\Delta m_A^2|} (1 - 2 \sin^2 \theta_{12}). \quad (3)$$

If the inverted ordering is to be ruled out, limits below $\langle m_{ee} \rangle_{\min}^{\text{IH}}$ have to be reached. Among the parameters governing $\langle m_{ee} \rangle_{\min}^{\text{IH}}$ the largest dependence is induced by the solar neutrino parameter $\sin^2 \theta_{12}$, and quantifies to an uncertainty of about a factor of 2 for $\langle m_{ee} \rangle_{\min}^{\text{IH}}$. This factor of 2 introduces therefore about the same uncertainty as the nuclear matrix elements (NMEs), and motivates solar neutrino precision experiments in order to reduce it.

The three types of neutrino mass observables are obviously highly complementary. Ordinary beta decay is basically a model-independent probe of neutrino mass, whereas the extraction of the cosmological observable $\sum m_i$ is sensitive to the data sets used, and little is known what happens to limits when non-standard cosmological models different from the Λ CDM framework are applied. As mentioned above, neutrino mass limits from $0\nu\beta\beta$ require the assumption of lepton number violation and in addition, as we will see below, that no other mechanism contributes.

At the end of this decade, m_β will be known to be larger or smaller than about 0.3 eV, standard cosmology will be sensitive to smaller values of $\sum m_i$, while $\langle m_{ee} \rangle$ can also be probed down to the 0.1 eV regime. All three observables

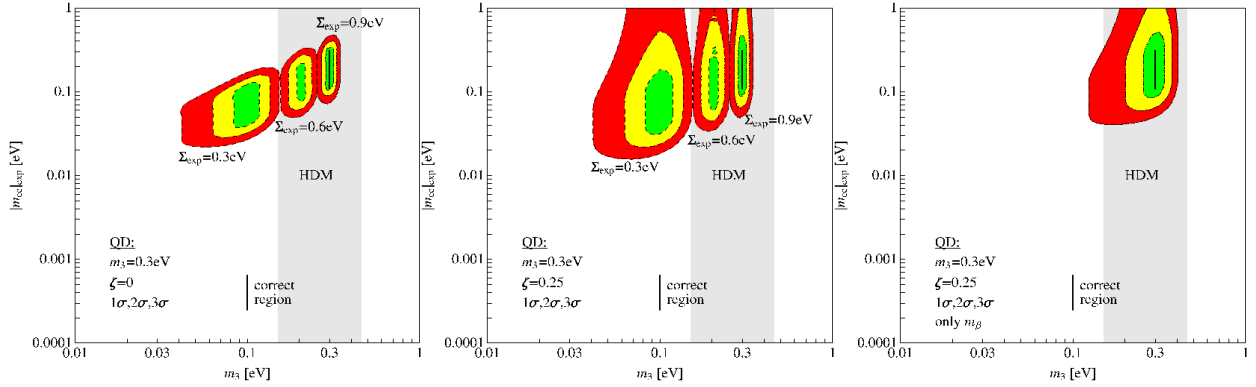


Figure 2: 1, 2 and 3σ regions in the m_3 - $\langle m_{ee} \rangle_{\text{exp}}$ plane for a true value of $m_3 = 0.3$ eV. The solid line is the correct region. The left plot is for no NME uncertainty, the middle and right plots for $\zeta = 0.25$. Three different measured values of Σ are assumed for the left and middle plots. In the right plot the cosmological mass limit is left out of the analysis. The area denoted HDM is the range of $\langle m_{ee} \rangle$ from the claim of part of the Heidelberg-Moscow collaboration. Taken from [12].

are therefore expected to be tested at similar levels, and the complementarity of the different approaches to neutrino mass opens up exciting possibilities. The interplay of the observables is studied in detail e.g. in Refs. [6, 7, 8, 9, 10]. The ideal case would arise when positive signals in all three measurements were found. Using the foreseen experimental uncertainties (and theoretical uncertainties, i.e. the NMEs) one can estimate how precisely the neutrino mass scale could be pinned down [11, 12]. The following analysis, taken from Ref. [12] (similar results can be found in [11]), assumes quasi-degenerate neutrinos with a true value of the neutrino mass of $m_3 = 0.3$ eV (hence $m_\beta = 0.3$ eV and $\sum m_i = 0.91$ eV) and experimental errors as specified in publications of the respective collaborations. The remaining free parameter is called $\zeta \geq 0$ and quantifies the uncertainty introduced by our ignorance about the NMEs in the extraction of $\langle m_{ee} \rangle$ from a lifetime measurement. Without any NME uncertainty we could determine m_3 at 3σ to about 15 %, while $\zeta = 0.25$ would make this possible to 25 %. Leaving $\sum m_i$ out of the analysis would lead to an error of 50 % on m_3 if $\zeta = 0.25$, which illustrates that the precision is largely from the determination of $\sum m_i$. This is all illustrated in Fig. 2, which displays the reconstructible 1, 2 and 3σ contours in the parameter space of m_3 and the measured effective mass $\langle m_{ee} \rangle_{\text{exp}}$.

Another aspect of mass-related observables is the potential to rule out some of the many models which have been proposed to explain lepton mixing. Very often flavor symmetry models generate neutrino mass sum-rules (see e.g. [13]) and thereby generate relations between the observables that are different from the general case (Fig. 1) and therefore only certain regions in parameter space are allowed. Fig. 3, taken from Ref. [14], shows the result for four sum-rules.

Before turning to non-standard interpretations, i.e. mechanism of double beta decay not directly connected to 3 neutrino oscillations, let us mention an “intermediate case”: if light sterile neutrinos exist, which could be suggested by interpretations of the LSND/MiniBooNE experiments (see [15] for their current status), then there are eV scale sterile neutrinos with mixing angles of order 0.1. Hence, their contribution to the effective mass [16] is at least of order 0.01 eV, i.e. of the same order as for the inverted hierarchy.

3. Non-Standard Interpretations

A clear experimental signature for a non-standard contribution to $0\nu\beta\beta$ would be for instance no signal in KATRIN and/or cosmology, and a life-time measurement in $0\nu\beta\beta$ which would be interpreted as an effective mass of 0.5 eV or so. There are several candidates for non-standard contributions: Higgs triplets, right-handed currents, heavy Majorana neutrinos, supersymmetric particles, etc. Limits from $0\nu\beta\beta$ can be translated into limits on the couplings and masses associated with these mechanisms. The limits from the literature, which often take nuclear physics aspects into

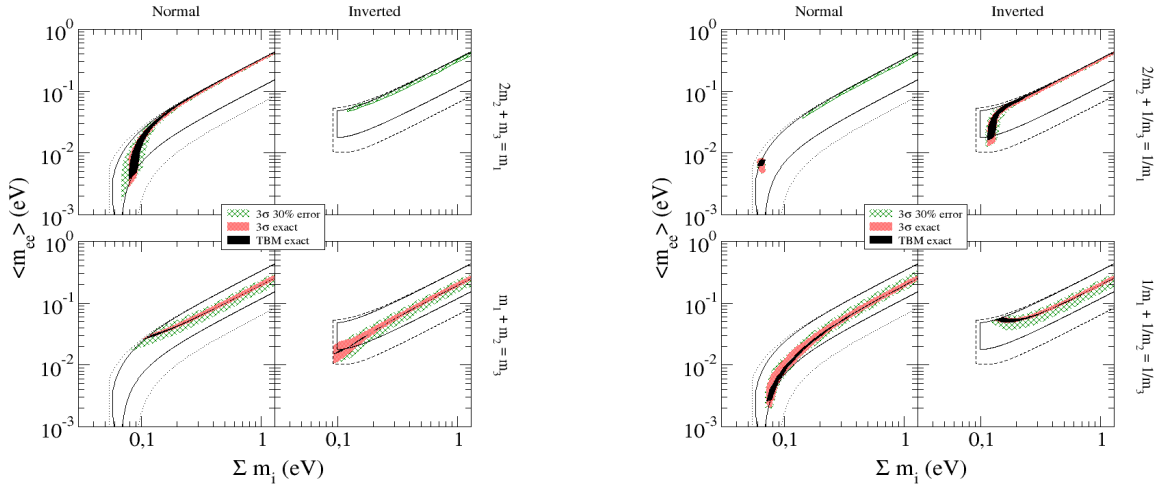


Figure 3: Allowed regions in $\langle m_{ee} \rangle - \sum m_i$ parameter space for the sum-rules $2m_2 + m_3 = m_1$ (top left), $m_1 + m_2 = m_3$ (bottom left), $\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$ (top right) and $\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$ (bottom right). The regions allowed in the general case are indicated by the black lines. Neutrino masses are here understood to be complex. Taken from [14].

account, can be approximately reproduced by rather simple arguments on the amplitude level. For instance, heavy Majorana neutrinos (for which in the propagator the limit $M_i^2 \gg q^2$ applies) will have an amplitude proportional to $\mathcal{A} \propto G_F^2 \frac{S_{ei}^2}{M_i^2}$, where M_i are heavy neutrino masses with coupling S_{ei} to electrons. Setting this amplitude equal to the light neutrino amplitude from Eq. (1), and using $\langle m_{ee} \rangle \lesssim 0.5$ eV gives $S_{ei}^2/M_i^2 \lesssim 5 \times 10^{-8} \text{ GeV}^{-1}$, which is in fact the limit given in [17]. (Left-handed) Higgs triplet exchange has an amplitude $\mathcal{A} \propto G_F^2 h_{ee} v_L / M_\Delta^2$, where h_{ee} is its coupling to two electrons, v_L its vev, and $M_\Delta \gg q$ its mass. Note that $h_{ee} v_L$ is the contribution of the triplet to neutrino mass. Therefore, if the triplet would be responsible for neutrino mass, its contribution to $0\nu\beta\beta$ would be suppressed by a factor q^2/M_Δ^2 . On the other hand, the triplet can only give the leading contribution to $0\nu\beta\beta$ if $\langle m_{ee} \rangle$ is extremely small.

R -parity violating SUSY can also mediate the process (see e.g. [18, 19]), in two classes of diagrams. First, in the usual diagram of $0\nu\beta\beta$ the W bosons can essentially be replaced by selectrons and the Majorana neutrino by a neutralino or gaugino. The amplitude is then given by $\mathcal{A} \propto g^2 \frac{\lambda_{111}^2}{\Lambda_{\text{SUSY}}^5}$, where $g \simeq \sqrt{0.1}$ is a (combination of) gauge coupling(s), λ_{111} stems from the vertex of the selectron with the up- and down quarks and the power of Λ_{SUSY} is easily understood by the propagators for one fermion and two bosons, whose masses are assumed to be $\Lambda_{\text{SUSY}} \gg q$. By comparing again with the amplitude in Eq. (1), it follows $\frac{\lambda_{111}^2}{\Lambda_{\text{SUSY}}^5} \lesssim 7 \times 10^{-17} \text{ GeV}^{-5}$, to be compared with the literature value of $3 \times 10^{-17} \text{ GeV}^{-5}$ [19]. Interestingly, the same couplings describe resonant selectron production at the LHC [20], which allows to test this mechanism¹. For instance, one can show that certain regions in SUSY parameter space are in conflict with existing $0\nu\beta\beta$ -limits, or that detection of resonant selectron production at the LHC in other regions would rule out any considerable contribution of this mechanism to $0\nu\beta\beta$ [20]. Another class of R -parity violating diagrams involves neutrino and virtual squark exchange. The amplitude goes as $\mathcal{A} \propto G_F m_{d_k} \frac{\lambda'_{1k1} \lambda'_{11k}}{q \Lambda_{\text{SUSY}}^3}$, where m_{d_k} is the down-type quark mass of the k th generation. It enters the game because mixing between left- and right-handed squarks is involved, which is proportional to this mass. The $\lambda'_{121} \lambda'_{112}$ term is irrelevant due to K^0 - \bar{K}^0 constraints, and the $\lambda'_{111} \lambda'_{111}$ contribution is sub-leading with respect to the diagram discussed above [22]. Anyway, depending on whether it is the down-, strange- or bottom (s)quark, by comparing the amplitudes limits of $(1 \times 10^{-11}, 6 \times 10^{-13} \text{ or } 1 \times 10^{-14}) \text{ GeV}^{-3}$ arise, compared with the actual literature values of $(7.7 \times 10^{-12}, 4.0 \times 10^{-13} \text{ or } 1.7 \times 10^{-14}) \text{ GeV}^{-3}$.

¹LHC related phenomenology of non-standard mechanisms in left-right symmetric theories has recently been discussed in [21].

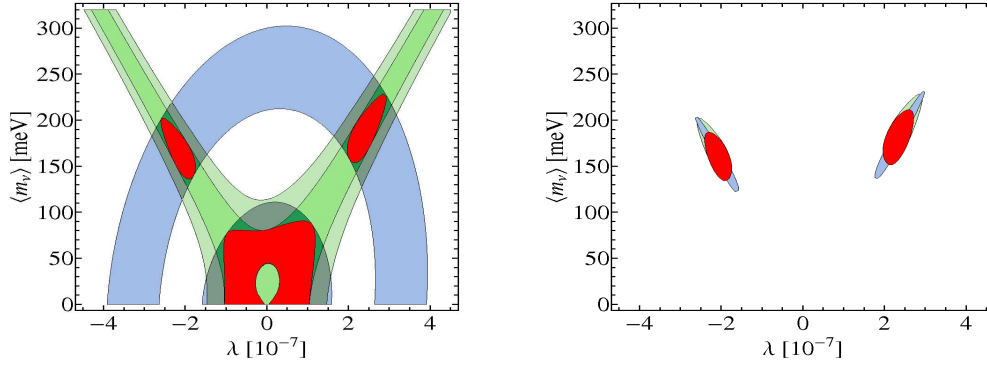


Figure 4: Left: constraints at 1σ on the model parameters from an observation of $0\nu\beta\beta$ of ^{82}Se at half-life 10^{25} y (outer blue elliptical area) and 10^{26} y (inner blue elliptical area). Adding the reconstruction of the angular (outer, lighter green) and energy difference (inner, darker green) distribution drastically shrinks the allowed parameter space. Right: adding information from the decay of ^{150}Nd . In this example, 30 % admixture of right-handed currents is assumed. Taken from [27].

[23]. Again, the simple estimates are rather close to the limits involving nuclear physics.

However, there is nuclear physics, and in fact it can help to distinguish the different mechanisms. This has been dealt with recently in Refs. [24, 25, 26]. For instance, one can within a typical NME calculation fix the particle physics parameters such that for ^{76}Ge the life-time is the same for all popular non-standard mechanisms. Triggered by nuclear details, the life-time in other nuclei can however differ by up to one order of magnitude. Typically, multi-isotope determination of $0\nu\beta\beta$ in three to four different elements is necessary in order to single out the true mechanism [24].

We have seen up to know that non-standard mechanisms can be pinned down either by looking for other places in which they show their presence, or by probing $0\nu\beta\beta$ in different nuclei. The third possibility is to take a closer look at the decay products, namely the two final state electrons. The SuperNEMO experiment is currently the only one able to probe in particular the energy of the individual electrons and their angular distribution [27]. A recent analysis by the collaboration assumes the simultaneous presence of the standard mechanism (with the particle physics parameter $\langle m_{ee} \rangle$) and a right-handed current contribution ($\lambda = (m_W/m_{W_R})^2 U_{ei} V_{ei}$, with V being the right-handed analogon of the PMNS matrix). Fig. 4 shows an example of the results from [27].

4. Summary

Neutrinoless double beta decay will be intensively searched for in the current decade. The interesting complementarity with the other neutrino mass-related observables can shed some light on the question of neutrino mass generation and on the cosmological model. Perhaps even more interesting is the possibility of other mechanisms leading to $0\nu\beta\beta$, which have phenomenological consequences in a variety of fields, such as lepton flavor violation or accelerator physics.

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